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# The effects of aquaculture production noise on the growth, condition factor, feed conversion, and survival of rainbow trout, *Oncorhynchus mykiss*

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ABSTRACT

Intensive aquaculture systems, particularly recirculating systems, utilize equipment such as aerators, air and water pumps, blowers, and filtration systems that inadvertently increase noise levels in fish culture tanks. Sound levels and frequencies measured within intensive aquaculture systems are within the range of fish hearing, but species-specific effects of aquaculture production noise are not well defined. Field and laboratory studies have shown that fish behavior and physiology can be negatively impacted by intense sound. Therefore, chronic exposure to aquaculture production noise could cause increased stress, reduced growth rates and feed conversion efficiency, and decreased survival. The objective of this study was to provide an in-depth evaluation of the long term effects of aquaculture production noise on the growth, condition factor, feed conversion efficiency, and survival of cultured rainbow trout, *Oncorhynchus mykiss*. Rainbow trout were cultured in replicated tanks using two sound treatments: 117 dB re 1 μPa RMS which represented sound levels lower than those recorded in an intensive recycle system and 149 dB re 1 μPa RMS, representing sound levels near the upper limits known to occur in recycle systems. To begin the study mean fish weights in the 117 and 149 dB tanks were 40 and 39 g, respectively. After five months of exposure no significant differences were identified between treatments for mean weight, length, specific growth rates, condition factor, feed conversion, or survival ($n=4$). Mean final weights for the 117 and 149 dB treatments were 641 ± 3 and 631 ± 10 g, respectively. Overall specific growth rates were equal, i.e. 1.84±0.00 and 1.84±0.01%/day. Analysis of growth rates of individually tagged rainbow trout indicated that fish from the 149 dB tanks grew slower during the first month of noise exposure ($p<0.05$); however, fish acclimated to the noise thereafter. This study further suggests that rainbow trout growth and survival are unlikely to be affected over the long term by noise levels common to intensive aquaculture systems.



## 1. Introduction

Recently, there has been increasing concern regarding the effects of anthropogenic noise on marine life, including fish (Popper, 2003). A number of field and laboratory studies evaluating the effects of sound on fish have shown that increased ambient sound levels could alter habitat selection, behavior, and ecology, (Pearson et al., 1992; Knudsen et al., 1994; Engås et al., 1996; Sand et al., 2000; Tolimieri et al., 2002; Popper, 2003) and can cause negative effects on fish physiology such as hearing damage (Popper and Clarke, 1976; Enger, 1981; Hastings et al., 1996; Sverdrup et al., 1994; Scholik and Yan, 2001, 2002; Amoser and Ladich, 2003; McCauley et al., 2003), stress response (Santulli et al., 1999; Smith et al., 2004; Wysocki et al., 2006), and reduced growth rates (Sun et al., 2001). However, only a limited number of studies have investigated the effects of noise on fish physiology, growth, and survival within fish culture systems, particularly recycle systems that are known to produce relatively loud ambient sound levels.

Cultured fish could also be exposed to increased ambient noise, especially in large, commercial scale aquaculture facilities that utilize recirculating systems. In many aquaculture operations fish are confined to individual culture tanks where they cannot escape from areas with less than optimal sound conditions. Therefore, chronic exposure to elevated sound levels in aquaculture is a concern. However, only a few studies have investigated the effects of sound on cultured species. Banner and Hyatt (1973) observed lower egg viability and reduced growth rates for longnose killifish, *Fundulus similis*, and the sheepshead minnow, *Cyprinodon variegates*, when sound levels within aquarium tanks were approximately 20 dB higher than sound levels in control tanks. Lagardère (1982) and Regnault and Lagardère (1983) reported reduced growth and reproductive rates and decreased survival of cultured brown shrimp, *Crangon crangon*, when ambient sound pressure levels (SPLs) were 30 dB higher than SPLs

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common to the natural habitat of the brown shrimp. Additionally, Terhune et al. (1990) observed decreased growth and smoltification rates of Atlantic salmon, *Salmo salar,* in fiberglass tanks that had underwater sound levels 2–10 dB re 1 μPa higher at 100–500 Hz than concrete tanks. Although the following study evaluated an artificial sound stimulus that is uncharacteristic of aquaculture systems it is important to mention that Papoutsoglou et al. (2007) observed increased growth rates and lower levels of stress-related brain neurotransmitters in common carp, *Cyprinus carpio*, when Mozart music was transmitted to culture tanks under certain light conditions.

Recently, Wysocki et al. (2007b) found that the hearing, growth, survival, and disease resistance of rainbow trout (*Oncorhynchus mykiss*), which are commonly cultured within potentially noisy recycle systems, were not negatively impacted by long-term exposure to intensive aquaculture production noise (115, 130, and 150 dB re 1 μPa RMS). However, anecdotal evidence from Wysocki et al. (2007b), such as decreased feeding and slightly slower growth rates, particularly at the onset of noise exposure, warranted further investigation into the effects of aquaculture production noise on rainbow trout growth. These observations were not reported in Wysocki et al. (2007b) since a small sample size ($n=2$) made it difficult to determine if the suspected effects on growth were real. Therefore, the objective of the present study was to further evaluate the potential impacts of intensive aquaculture production noise on rainbow trout growth and survival. The present study was complementary to Wysocki et al. (2007b) and was conducted to provide a comprehensive assessment of the effects of aquaculture production noise on rainbow trout growth and survival including an evaluation of monthly and long term growth, specific growth rates, feed conversion efficiency, condition factor.

## 2. Materials and methods

Methods for the current study resembled those used in Wysocki et al. (2007b). To summarize, sound recordings were taken in a commercial scale (9.1 m diameter, 2.4 m deep) round fiberglass aquaculture tank within a recirculating system at the Freshwater Institute (Shepherdstown, WV). The recordings were representative of the sound characteristics that fish are exposed to within intensive recycle systems. A five minute audio recording was then created to simulate underwater sound characteristics recorded in the commercial scale tank and was burned to a CD. The audio recording was transmitted to the experimental tanks continuously, 24 h per day, via amplifiers (MPA-250, Radio Shack), a stereo sound mixer (Model 32-2057, Radio Shack), and tactile speakers (Model AW339, Clark Synthesis Tactile Sound, Littleton, CO) mounted on the outside walls of the tanks at mid depth (i.e. 38 cm from the top of the water column).

Eight round fiberglass tanks within a flow through system (1.5 m diameter, 0.8 m deep) were used in the current study. These tanks were within a culture area with the least ambient noise as compared to the rest of the facility. All tanks were designed to buffer ambient sound by eliminating contact between vibrating pipes and tank surfaces and by using insulating padding beneath tanks and around PVC pipes (Davidson et al., 2007). The study design consisted of four control tanks which received ambient noise only and had a mean sound level of 117±1 dB re 1 μPa RMS and four experimental tanks in which the sound system was tuned to produce mean sound levels of 149±0 dB re 1 μPa RMS. Bart et al. (2001) measured sound levels of 153 dB re 1 μPa in fiberglass tanks within a recirculating system. The highest sound levels reported within aquaculture systems are 160 dB re 1 μPa (Clark et al., 1996). Therefore, the treatment categories represented sound levels that were much lower than those recorded within recirculating systems and sound levels that were near the upper limits known to occur in intensive aquaculture production systems.

Fertilized rainbow trout eggs (*O. mykiss*) were obtained from a commercial fish hatchery and egg supplier (Troutlodge, Sumner, WA). The fish were all female diploids and the progeny of a cross between rainbow trout (the stationary freshwater form of *O. mykiss*) and steelhead trout (the anadromous form of *O. mykiss*), i.e. the same strain that was used in Wysocki et al. (2007b). The fertilized eggs were received at the Freshwater Institute at 3 °C, acclimated to hatching system temperatures (12 °C), and then divided into Heath incubator trays. Day 1 of the life cycle was designated when 50% of the eggs had hatched, six days after arrival. When fish had absorbed the majority of the yolk sac they were stocked into a single round tank (1.1 m diameter, 0.5 m maximum depth) also designed to buffer ambient sound to ensure that fish were not predisposed to sound levels that were significantly greater than the controls (117 dB re 1 μPa). Fish were fed a standard trout diet (Zeigler Brothers Inc., Gardners, PA) during the pre-study period. Daily feed rations and feed size were determined using standard trout feeding charts as well as observations of feeding activity. As the fish grew, water depth was gradually increased and fish were split into three identical tanks.

To begin the study 200 fish (39±0.2 g) were randomly divided into the experimental tanks at a density of 5.6 kg/m$^3$. Passive integrated transponder (PIT) tags (Biomark Inc., Boise, ID) were implanted in 100 fish from each tank in order to track individual growth rates during the study. Preliminary tagging studies at the Freshwater Institute and other recent studies suggest that rainbow trout retain tags well and have unaffected growth and survival rates (Acolas et al., 2007). The 11 mm, 125 kHz tags were implanted in the peritoneal cavity using hypodermic needles inserted behind the right pelvic fin of each fish. Needles were disinfected in an iodine solution after each use. To avoid bias, fish that were not implanted with PIT tags were punctured with the tagging syringes in the same location. Fish were allowed a one week acclimation period to adjust to the new tanks before the sound was initiated. A 1% salt treatment was administered for 30 min as a static bath one time per day for four days following tagging and stocking. Fish were kept off feed over the four day period as an additional measure to minimize stress.

Sound levels to the tanks were tuned prior to stocking to achieve approximately 150 dB re 1 μPa then equipment was turned off with the desired settings in place. The sound recording was turned on to the tanks sequentially so that video could be collected for each tank to observe initial fish response to the sound. Sound pressure level (SPLs) measurements were taken weekly to ensure that sound levels were consistent throughout the study. SPLs were extrapolated from millivolt readings which were collected using a calibrated hydrophone (HTI-94-SSQ, frequency response: 2–30 kHz, sensitivity: −170 dB re 1 V/μPa, High Tech Inc. Gulfport, MS) connected to a voltmeter. Raw voltage values were converted to broadband sound levels and expressed as dB re 1 μPa root mean squared (RMS). Sound levels (RMS) for each tank were measured using a grid system that consisted of 15 locations: five horizontal (5, 38, 76, 38, and 5 cm from the sides of the tank) and locations at 3 depths (5, 38, and 71 cm deep). In addition, a weekly 15 s sound recording was taken 38 cm from the side of the tanks at a depth of 38 cm to ensure that the spectral composition of the noise remained consistent over time. Recordings were made using the hydrophone connected to a low-pass filter set to 2000 Hz (Model 91149A, Precision Filters, Inc., Ithaca, NY), a pre-amplifier (Model FP-11, Shure Inc., Niles, IL), and an analog-to-digital converter and data logger (Model USB-9215, National Instruments, Austin, TX) connected to a laptop computer. Characterization of sound spectra and corresponding sound pressure levels were performed with NI-DAQmx Base Software using a Labview 7.1 application (National Instruments, Austin, TX).

The study was conducted over a five month period and concluded when the fish reached maximum densities, approximately 80 kg/m$^3$. Fish were cultured well beyond the generally accepted market size of 340+ g (Fornshell, 2002) to simulate a complete production cycle and beyond. Throughout the study, all fish were cultured under a constant 24 h photoperiod at 13.0±0.0 °C. Fish were fed slow-sinking trout feed (Zeigler Brothers Inc., Gardners, PA) with a protein-to-fat ratio of 42/16 via automated feeders (Sterner Products AB, Sweden) programmed

**Table 1**
Mean sound levels (dB re 1 µ Pa RMS) for the 117 dB treatment

| | Distance from tank side (cm) | | | | |
|---|---|---|---|---|---|
| Depth (cm) | 5 | 38 | 76 | 38 | 5 |
| 5 | 120 | 110 | 110 | 110 | 120 |
| 38 | 122 | 115 | 113 | 115 | 124 |
| 76 | 123 | 116 | 115 | 117 | 124 |

to deliver the same amount of feed to each tank and were calibrated weekly. The feeding schedule consisted of 24–30 small feed events per day at equally spaced intervals around the clock. Flow rates were adjusted to maintain equal flow between treatments. Mean flow rates for the 117 and 149 dB treatments were 37.6±0.3 and 36.9±0.1 L/min, respectively. Water samples were collected on a monthly basis and analyzed for alkalinity, carbon dioxide, nitrite, total ammonia nitrogen, and total suspended solids. Dissolved oxygen and temperature were measured three times per week. Weights and fork lengths of all trout from each tank were measured monthly. During sampling events each fish was scanned using a PIT tag reader (Destron Mini Portable Reader, Destron Fearing Corporation, St. Paul, MN). Tag codes were stored within the PIT tag reader, downloaded to an excel file, and matched with respective length and weight data to track individual growth rates. In order to retrieve data for all tagged fish, every fish in each tank was sampled; therefore population means for length and weight were obtained as opposed to sample means. Individual weights were not collected during the third monthly length and weight sample due to problems with the PIT tag reader.

Statistical analyses were performed using Systat 11 software (Systat Software, Inc., 2004). Multivariate repeated measures analysis of variance (MANOVA) was used to test for differences in weight, length, condition factor, and feed conversion ratios between treatments. Each tank was considered an experimental unit, therefore tank means ($n$=4) were used to test for differences between treatments. The experimental design provided a 99% chance of detecting a 10% difference between treatments. To further investigate potential subtle differences in growth between treatments, growth rates of individually tagged fish from each treatment were pooled and also compared using MANOVA ($n$=342,325). Post hoc analysis for individual growth rates was conducted using separate $t$-tests for each weight sample with a Bonferroni adjustment of the probability threshold ($\alpha$), which is used when making multiple comparisons on a data set to reduce the chance of Type I error. The Bonferroni adjustment was calculated as the original probability threshold / the number of weight samples: $\alpha$=(0.05/ 5)=0.01. A Mann–Whitney $U$-test was used to test for differences in survival between treatments. Survival efficiencies were transformed for statistical analysis using an arcsine square-root transformation (Sokal and Rohlf, 1981). A probability level ($\alpha$) of 0.05 was used to determine significance for each statistical test, with the exception of the post hoc analysis of individual growth rates ($\alpha$=0.01). In addition, 95% confidence intervals were applied to monthly weight and length measurements. The following criteria were calculated and used for analysis: 1) Percentage difference in mean weights and lengths between treatments (PD %)=(($Wt_{117\ dB}$−$Wt_{149\ dB}$)/$Wt_{117\ dB}$)*100; specific growth rates (SGR, %/day)=((LN ($Wt_f$)–LN($Wt_i$))/days between samples)*100; Fulton's condition factor (CF)=($10^5$* $Wt_{(g)}$)/$L^3_{(mm)}$ (Lagler, 1956); and feed conversion ratio (FCR)=(Total Feed $Dispensed_{(kg)}$/Total Biomass $Gained_{(kg)}$)*100.

**Table 2**
Mean sound levels (dB re 1 µ Pa RMS) for the 149 dB treatment

| | Distance from side of tank (cm) | | | | |
|---|---|---|---|---|---|
| Depth (cm) | 5 | 38 | 76 | 38 | 5 |
| 5 | 157 | 135 | 133 | 139 | 164 |
| 38 | 157 | 143 | 140 | 147 | 163 |
| 76 | 157 | 142 | 142 | 146 | 163 |

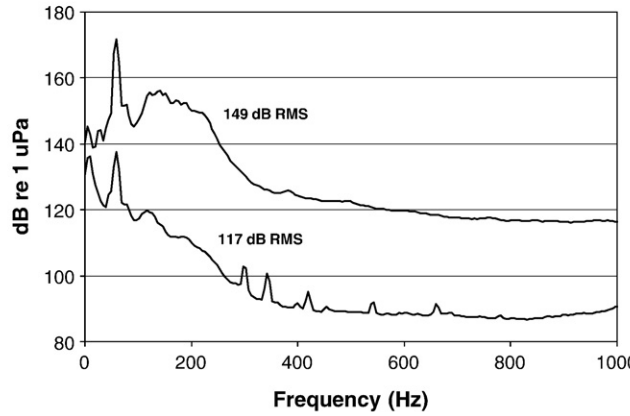


**Fig. 1.** Mean sound spectrum levels for the two sound treatments.

## 3. Results

### 3.1. Experimental conditions

Mean sound levels for the control tanks and the experimental tanks were 117±1 dB re 1 µPa RMS and 149±0 dB re 1 µPa RMS, respectively. Sound pressure levels generally varied depending on location within the tanks, with the loudest areas closest to the side walls and the bottom of the tank, and quietest locations near the top and center of the tanks (Tables 1 and 2). Mean spectral plots for each treatment are presented in Fig. 1. There were significant differences between treatments for the following water quality parameters: total ammonia nitrogen, total suspended solids, and dissolved oxygen (Table 3). All water quality parameters were well within safe recommended limits (Colt and Tomasso, 2001) and the differences between treatments are small and therefore would not have impacted growth.

### 3.2. Observations

When the 149 dB treatment was initiated the fish responded with an initial alarm reaction, scattering throughout the tank and swimming erratically. Fish began swimming in normally distributed patterns within a few hours following the onset of the sound.

### 3.3. Growth (Weight)

Following random stocking rainbow trout weights were 39±0 and 40±0 g, for the 117 dB and 149 dB tanks, respectively (Fig. 2). Fish from the 117 dB tanks were slightly larger (1.5%), but not significantly larger ($p$=0.672), than fish from the 149 dB tanks to begin the study (Fig. 3).

**Table 3**
Mean water quality concentrations±1 standard error for each sound treatment

| Parameter | 117 dB | 149 dB |
|---|---|---|
| Alkalinity (mg/L) | 272±2 | 266±3 |
| Carbon dioxide (mg/L) | 21±1 | 21±0 |
| Dissolved oxygen (mg/L)[a] | 10.2±0.0 | 10.6±0.1 |
| Nitrite (mg/L) | 0.00±0.00 | 0.01±0.00 |
| Total ammonia nitrogen (mg/L)[a] | 0.38±0.00 | 0.36±0.00 |
| Total suspended solids (mg/L)[a] | 1.30±0.10 | 0.87±0.04 |

[a] Indicates significant difference between treatments. Note: All water quality parameters are within safe limits (Colt and Tomasso, 2001).

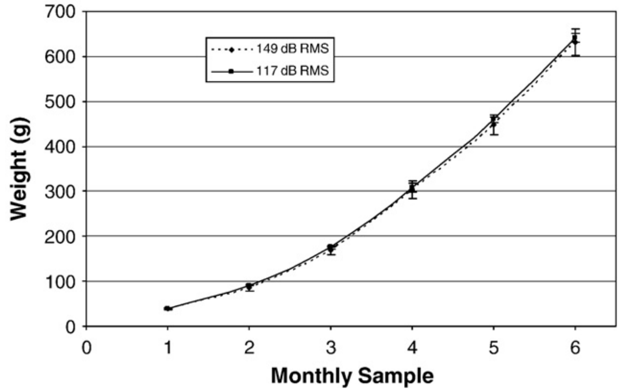


**Fig. 2.** Mean growth rates (g) for the 149 and 117 dB treatments throughout the study with 95% confidence intervals.

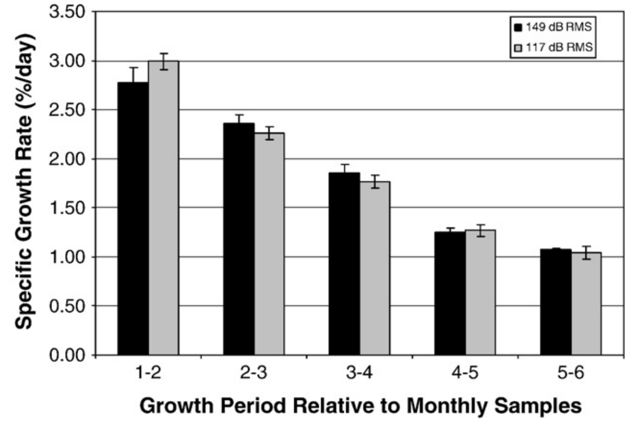


**Fig. 4.** Specific growth rates (% growth/day) between each monthly sample for the 149 and 117 dB treatments with 95% confidence intervals.

Following one month of noise exposure (sample 2), 95% confidence intervals for the 117 and the 149 dB treatments were 90–92 and 79–91 g, respectively, and barely overlapped. The 95% confidence intervals for specific growth rate also exhibited only slight convergence, i.e. 2.90–3.07%/day for the 117 dB treatment vs. 2.64–2.93%/day for the 149 dB treatment (Fig. 4). Following one month of exposure to experimental conditions mean weights were 91±0 g in the 117 dB tanks and 85±2 g in the 149 dB tanks (Fig. 2). Fish in the 117 dB tanks were 6.8% larger than the 149 dB tanks after one month, which was a notable increase from the 1.5% difference observed at the beginning of the study (Fig. 3).

There was no long term effect of noise exposure on rainbow trout growth. There were no significant differences in mean growth between the 117 and 149 dB treatments ($p$=0.204) and no significant differences relative to a time×treatment interaction ($p$=0.062). In addition, overall specific growth rates for the 117 and the 149 dB treatments were equal, 1.84±0.00 and 1.84±0.01, respectively (Table 4). Calculation of 95% confidence intervals indicated that weight intervals for the 117 and the 149 dB treatments overlapped at the conclusion of the study (i.e. 630–652 and 600–661 g, respectively) and for each monthly weight sample (Table 4; Fig. 2). The mean weight for the 117 dB treatment (641±3 g) was 1.6% greater than the 149 dB treatment (631±10 g), a non-statistical difference that essentially existed to begin the study (Table 4, Fig. 3).

### 3.4. Individual growth (Weight)

To further investigate potential subtle differences in growth between treatments, growth rates of individually tagged fish from each treatment were pooled and compared using MANOVA. A significant difference existed in individual growth rates between the 117 and 149 dB treatments ($p$=0.035), as well as the time×treatment interaction ($p$=0.000). Post hoc analysis, testing against an $\alpha$=0.01 indicated that the difference in the time×treatment interaction occurred during sample 2 ($p$=0.000). Mean weights for sampling events 1, 4, 5 and 6 were not significantly different ($p$=0.024, 0.107, 0.019, 0.188, respectively).

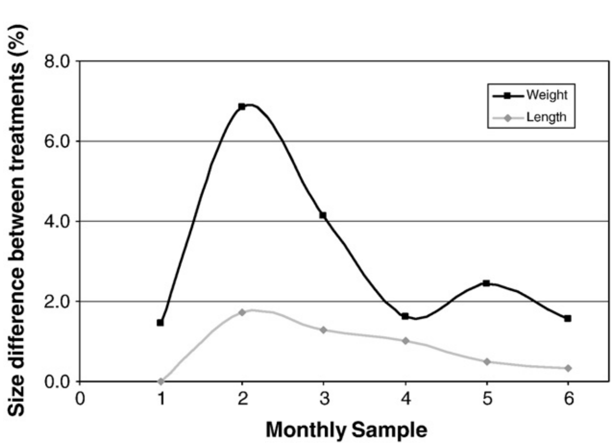


**Fig. 3.** Percentage difference in mean weights and lengths between treatments for each monthly sample.

### 3.5. Growth (Length)

Rainbow trout lengths at the beginning of the study were equal between treatments, 142±0 mm. Following one month of exposure to experimental conditions mean lengths were 175±1 mm in the 117 dB tanks and 178±1 mm in the 149 dB tanks (Fig. 5). Similar to the trend for fish weight, percentage difference in length peaked after the first month of the study and decreased during each subsequent sample (Fig. 3). There was no long term effect of noise exposure on rainbow trout growth relative to length. There were no significant differences in length between the 117 and 149 dB treatments ($p$=0.260) and no significant differences relative to a time×treatment interaction ($p$=0.358). Fish lengths at the end of the study for the 117 and the 149 dB tanks were 333±2 and 334±1 mm, respectively (Table 4, Fig. 5).

### 3.6. Condition factor

There were no significant differences in condition factor between treatments ($p$=0.431) and no time×treatment interaction ($p$=0.804) throughout the study. Rainbow trout condition factors for the 117 dB and the 149 dB tanks to begin the study were 1.36±0.01 and 1.37±0.01, respectively. Rainbow trout condition factors at the end of the study were 1.71±0.01 for the 117 dB treatment and 1.70±0.01 for the 149 dB treatment (Table 4).

**Table 4**
Mean±1 standard error for various growth criteria for the 117 and 149 dB treatments following five months of noise exposure ($n$=4)

| Parameter | 117 dB | 149 dB |
|---|---|---|
| Weight (g) | 641±3 | 631±10 |
| 95% CI Weight (g) | 630–652 | 601–662 |
| Length (mm) | 333±2 | 334±1 |
| Specific growth rate (%/day) | 1.84±0.00 | 1.84±0.01 |
| 95% CI SGR (%/day) | 1.83–1.86 | 1.82–1.87 |
| Feed conversion ratio | 1.07±0.01 | 1.09±0.02 |
| Condition factor | 1.71±0.01 | 1.70±0.01 |
| Survival (%) | 98.6±0.4 | 99.0±0.2 |

Note: There were no statistical differences between treatments for all parameters.

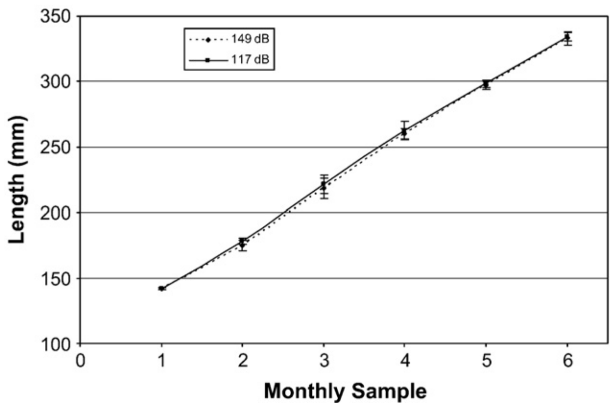


**Fig. 5.** Mean length (mm) for the 149 and 117 dB treatments throughout the study with 95% confidence intervals.

### 3.7. Feed conversion

There were no significant differences in FCR between treatments ($p=0.141$), but there was a significant difference relative to a time×treatment interaction ($p=0.001$). Similar to the aforementioned parameters, the greatest difference in FCR between treatments occurred during the first month of the study. After one month of noise exposure, FCRs were 0.88±0.02 in the 117 dB tanks and 1.01±0.04 in the 149 dB tanks. Feed conversion ratios for the 117 dB and the 149 dB treatments throughout the study were 1.07±0.01 and 1.09±0.02, respectively (Table 4).

### 3.8. Survival

There was no significant difference in percentage survival between the 117 and 149 dB treatments, i.e. 98.6±0.4 and 99.0±0.2%, respectively ($p=0.661$) (Table 4). Mean total mortality for the 117 dB was 3±1 fish and 2±0 fish for the 149 dB treatment. The sum of mortalities across all replicated tanks was 11 fish for the 117 dB treatment and 8 fish for the 149 dB treatment.

## 4. Discussion

Intensive aquaculture systems, particularly recycle systems, often utilize equipment such as aerators, air and water pumps, harvesters, blowers, and filtration systems that could increase ambient sound levels within culture tanks. Davidson et al. (2007) found that low frequency tonal sounds created by nearby pumps (59 Hz) and blowers (29 Hz) were transmitted into fish culture tanks and contributed to the loudest portion of the sound spectrum (105–130 dB re 1 μPa). Bart et al. (2001) found that mean broadband sound pressure levels (SPLs) differed between various intensive aquaculture systems. Mean SPLs ranged from <100 dB re 1 μPa in an earthen pond with the aerator turned off, 120 dB in concrete raceways, and 130 dB in round fiberglass tanks of various sizes. In the same study, SPLs were generally higher at relatively low frequencies (125–135 dB re 1 μPa at 25–1000 Hz) and ranged from 100–115 dB re 1 μPa at 1–2 kHz. Consequently, cultured fish are chronically exposed to noise levels that are well within the hearing range of many aquaculture species. Sound pressure levels within aquaculture systems are likely greater than underwater sound levels of most natural habitats. For example, Lugli et al. (2003) reported maximum sound pressure levels in streams and rivers of 85–110 dB re 1 from 60–500 Hz. Mean sound levels of 119 dB re 1 μPa have also been measured in creeks known to sustain rainbow trout (Wysocki et al., 2007a). Therefore, stream dwelling fish such as trout that are cultured within intensive recycle systems could be exposed to sound levels that are 40–75 dB re 1 μPa greater than sound levels experienced in a natural environment.

In the current study sound pressure levels at or above those normally encountered within intensive recirculating aquaculture systems had no effect on the long term production characteristics of rainbow trout. However, initial effects on growth, observed as anecdotal evidence during Wysocki et al. (2007b), were evident again during this study. Although significant differences were not detected for all growth parameters over the long term, data analyses indicated that rainbow trout in the 149 dB treatment were negatively affected during the first month of noise exposure and then acclimated to the increased sound over the remainder of the study. Observations of an initial startle response, confidence intervals for weight, plots of percent difference in length and weight, and higher FCRs for the 149 dB treatment each indicate that fish were negatively impacted during the first month of exposure to the 149 dB treatment. Due to a relatively small sample size ($n=4$), which was limited due to availability of resources, the study design was not powerful enough to statistically detect small differences, i.e., less than 10%.

To further simulate the potential difference in growth between treatments, growth rates of individually tagged fish from each treatment were pooled and compared. Results indicated a significant difference between treatments and a difference in the time×treatment interaction. Post hoc analysis indicated that the only significant difference in fish weight occurred for sample 2, after the first month of noise exposure. Therefore, analysis of individual growth rates provides further evidence of a subtle negative effect on growth for the 149 dB treatment over the first month of noise exposure. Individual fish typically are not analyzed as units of replication. Therefore, these results were not used in drawing overall conclusions, but to further analyze potentially small differences between treatments.

The subtle differences in growth and comparatively higher FCRs measured for the 149 dB treatment could be explained by several theories: 1) fish were not feeding as well as the 117 dB controls due to potentially stressful acoustic conditions or 2) fish were consuming similar amounts of food as control fish but utilizing some energy towards a physiological stress response rather than complete growth. Increased stress levels in fish, especially when chronic, could adversely affect growth, sexual maturation and reproduction, immune response, and survival in fish (Wedemeyer et al., 1990; Wedemeyer, 1996; Pickering, 1992; Wendelaar-Bonga, 1997; Weyts et al., 1999; Pankhurst and Van der Kraak, 2000).

Rainbow trout apparently were successful in physiological adaptation to any stress response caused by the 149 dB treatment as evidenced by the increased growth rates during the remainder of the study and excellent survival. Following the first month of noise exposure, specific growth rates for the 149 dB fish increased and were slightly faster than growth rates for the 117 dB treatment (samples 3 and 4, Fig. 4), indicating that the fish had adapted to potentially stressful conditions caused by the sound.

Minimal effects on rainbow trout growth evidenced in the current study and Wysocki et al. (2007b) are likely related to the hearing capability of rainbow trout. Previous studies have shown that salmonids do not have a wide hearing bandwidth or sensitivity to sound pressure levels and are therefore not as likely to be impacted by increased ambient sound. Hawkins and Johnstone (1978) discovered that Atlantic salmon, a hearing generalist, responded only to frequencies below 380 Hz, and Wysocki et al. (2007b) found that rainbow trout responded to sound stimuli up to 500 Hz. Additionally, Wysocki et al. (2007b) found that hearing thresholds of rainbow trout cultured under similar conditions, i.e. in tanks with SPLs of 150 dB re 1 μPa RMS, did not experience a shift in hearing threshold that would indicate hearing damage. Rainbow trout have been characterized as hearing generalists since they do not possess specialized hearing structures and therefore have a limited range of hearing sensitivity (Popper et al., 2003). Hearing generalists typically can only detect frequencies below 500 Hz and are not as sensitive to sound pressure levels (Popper, 2003). Many teleost species, such as carp and catfish possess physiological adaptations called Weberian ossicles, a bony connection that bridges the swim bladder and the inner ear that enhances hearing capability (Popper and Fay, 1973; Popper et al., 2003; Ladich and Popper, 2004). Most hearing specialists can detect sound pressure levels as low as 50–75 dB re 1 µPa, and frequencies ranging from 100–2000 Hz (Popper, 2003; Popper et al., 2003). Although rainbow trout growth and survival were not impacted over the long term during the present study, these results should not be generalized to all cultured species. Hearing specialist species such as catfish, goldfish, and carp are sometimes cultured in intensive aquaculture systems, including recycle systems (Broussard and Simco, 1976; Bovendeur et al., 1987; Ng et al., 1992; McVeigh, 2004; Halachmi, 2006).

## 5. Conclusions

In conclusion, intensive aquaculture production noise, particularly sound levels associated with recirculating systems, did not inhibit rainbow trout growth and survival over the greater part of a production cycle. Thus, results from the current study corroborate the findings of Wysocki et al. (2007b). Although significant differences in rainbow trout growth were not detected in the current study, comprehensive data analysis showed that rainbow trout did appear to exhibit a stress response when the 149 dB sound was initiated but appeared to acclimate to the increased sound. Any effects of noise during the study appear to be subtle; however, management of noise associated with intensive aquaculture systems should still be considered. In standard aquaculture production fish could experience circumstances similar to those that were presented during this study in which they are suddenly exposed to increased sound levels. Although fish in the current study acclimated to the increased sound, decreased immune efficiency and disease could have resulted in the presence of additional stressors, such as poor water quality, poor handling, or crowded conditions. Therefore, production system noise should be considered as a variable that requires control. Some aquaculture facilities are designed with rooms that separate pumps, blowers, and other unit processes from culture areas to minimize noise transmission into tanks. Davidson et al. (2007) suggests some practical and inexpensive methods to reduce sound levels within fish culture tanks.

This study evaluated a continuous, i.e. unchanging sound stimulus, to which rainbow trout appeared to acclimate. Rainbow trout could have responded differently to irregular sound patterns, such as loud bursts of sound, which often occur in aquaculture facilities due to construction, use of power tools, and the operation of equipment related to harvesting and cleaning. Therefore, additional research simulating intense bursts of aquaculture noise would be beneficial. Additionally, this study did not evaluate the effects of production noise on rainbow trout during the early developmental life stages. Therefore, additional research is necessary to determine the long term effects of aquaculture production noise on rainbow trout eggs and larvae as well as many other cultured species, particularly fish with hearing specializations.

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